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Mehto, Varpu

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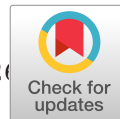
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Epistemic roles of materiality within a collaborative invention project at a secondary school

Varpu Mehto , Sini Riikonen , Kai Hakkarainen , Kaiju Kangas  and Pirita Seitamaa-Hakkarainen 

Varpu Mehto is a doctoral student at the University of Helsinki, Faculty of Educational Sciences. Her research interests focus on sociomateriality and embodiment in collaborative design and innovation processes. Sini Riikonen is a doctoral student at the University of Helsinki, Faculty of Educational Sciences. Her research interests focus on collaborative design and innovation processes, knowledge creation and learning through collaborative design. Kai Hakkarainen (PhD) is a professor of Education at the University of Helsinki, Faculty of Educational Sciences. For 20 years, Hakkarainen has investigated personal and collaborative learning processes at all levels, from elementary to higher education, with his colleagues. Kaiju Kangas (PhD) is an assistant professor of Technology Education at the University of Helsinki, Faculty of Educational Sciences. Her research focuses on the learning of design and technology in basic education and teacher education, as well as on the mediated and embodied nature of learning. Pirita Seitamaa-Hakkarainen (PhD) is a professor of Craft Science at the University of Helsinki, Faculty of Educational Sciences. Her research interests focus on design processes as well as the facilitation of collaborative design through technology-enhanced learning. Address for correspondence: Varpu Mehto, Faculty of Educational Sciences, University of Helsinki, P.O. Box 8, 00014, Finland. Email: varpu.mehto@helsinki.fi

Abstract

In this study, we examined maker-centred learning from an epistemic perspective, highlighting the agentic role of material engagement and artefacts in learning and creativity. The use of physical materials plays a crucial role in maker activities where the socio-epistemic aspects of knowledge creation entangle with the designing and making of physical artefacts. By taking a case study perspective, we analysed video data from nine design sessions involving a team of students (aged 13 to 14) developing an invention. First, we analysed knowledge that was built during the process. Our analysis revealed how design ideas evolved from preliminary to final stages and, together with the expressed design problems and conversations preceding the ideas, formed an epistemic object pursued by the team. Next, we included non-human agencies into the analysis to understand the role of materials in the process. Features of materials and human design intentions both constrained and enabled idea improvement and knowledge creation, intermixing meanings and materials. Material making invited the students to not only rely on human rationalisation, but also to think together with the materials.

Introduction

Maker-centred learning through collaborative inventing engages students in open-ended design and making processes. These are characterised by iterative efforts to solve complex problems, overcome obstacles and fail repeatedly, obtain peer and expert feedback, try again and end up with outcomes that may not have been anticipated in the beginning. In maker-oriented study projects, the epistemic aspects of knowledge-creation are sociomaterially entangled with the designing and making of physical artefacts (Latour, 2007; Orlikowski, 2007). Together with several schools in Finland, we have conducted invention projects that aimed to engage students in

Practitioner Notes

What is already known about this topic

- Advanced collaboration requires group members to focus on a shared object that they jointly construct during the design process.
- The importance of participating in embodied design activities and working with tangible artefacts is emphasised.
- Social and material aspects are constitutively entangled, and non-human components perform an active and dynamic role in actions.

What this paper adds

- While collaboratively developing an invention, the team had to handle versatile and sophisticated epistemic issues, ranging from making a tangible object to theoretical scientific concepts.
- Materials had an active role, as the involved artefacts affected which questions could be asked, and the material making rooted the ideation process in the tangible world.

Implications for practice and policy

- Participation in a collaborative invention project fosters students' personal and social learning engagement. It also elicits skills in solving non-routine problems and productively engaging in design and invention practices. Co-invention projects require a significant amount of innovative thinking and solving of complex design problems.
- Material making, together with an open-ended design task and unscripted sessions, provides possibilities for spontaneous experimentation and play, which allows for thinking together with the materials.

collaborative efforts to create complex artefacts, sparking intellectual, technical and aesthetic challenges (Riikonen, Seitamaa-Hakkarainen, & Hakkarainen, 2018). The projects were designed to offer the students ample opportunities for knowledge creation and innovative thinking.

We have taken a case-study perspective to shed light on the nature of sociomaterially entangled knowledge appearing in these nonlinear, intrinsically material projects. In our analysis of video data from one student team's invention process, we took two perspectives: epistemic and material. First, we empirically analysed the conceptual aspects of the students' envisioned epistemic object (Knorr Cetina, 2001). Then, to better understand the constraining and enabling roles of materiality, we included non-human agencies into our analysis by focusing on the reciprocal relationships among humans and nonhumans. From years of research and practical work in the field of craft, design and technology education, we have come to understand the importance of the physical materials (eg, Yrjönsuuri, Kangas, Hakkarainen, & Seitamaa-Hakkarainen, 2019). In this study, as we are searching for theoretically grounded methodologies that enable listening to materials, we draw from sociomaterial theories that guide us amidst nonlinearity and uncertainty (Braidotti, 2019) as well as constantly changing entanglements of human and non-human components (Barad, 2007).

Our analysis revealed how design ideas evolved, from preliminary to final stages and this allowed us to form a model of the created epistemic object. The ideation process was constitutively entangled (Orlikowski, 2007) with artefacts and the materiality of the project. The open-ended making task offered a possibility for spontaneous experiences with the materials.

Theory

Successful collaborative invention processes and associated efforts in creating knowledge require a team to identify the design problems related to the task, determine the constraints outlining the possible solutions, and actively engage in and take responsibility for the process (Lawson, 2004; Paavola & Hakkarainen, 2014; Sawyer, 2006; Scardamalia & Bereiter, 2014a). From the perspective of learning, many researchers have emphasised the importance of participating in embodied design activities and working with tangible artefacts (Blikstein, 2013; Kafai, 1996; Kangas, Seitamaa-Hakkarainen, & Hakkarainen, 2013; Kolodner, 2002). Collaborative invention relies on the concept of knowledge-creating learning that, beyond knowledge acquisition and social participation, involves systematic efforts in creating and advancing shared epistemic objects by externalizing ideas and constructing various types of intangible and tangible artefacts (eg, Paavola, Lipponen, & Hakkarainen, 2004; Scardamalia & Bereiter, 2014a). Knowledge creation is an emergent and nonlinear process where the actual goals, objects, stages, digital instruments and end results cannot be predetermined, nor can the flow of creative activity be rigidly scripted (Scardamalia & Bereiter, 2014b).

Previous studies on knowledge-creation processes suggest that advanced collaboration requires group members to focus on a shared object that they jointly construct during the design process (Barron, 2003; Hennessy & Murphy, 1999; Kangas *et al.*, 2013; Paavola & Hakkarainen, 2014; Seitamaa-Hakkarainen, Raunio, Raami, Muukkonen, & Hakkarainen, 2001). The knowledge-creation process may be perceived as guided and directed by envisioned epistemic objects that are incomplete and constantly being further defined and instantiated in a series of successively more refined visualizations, prototypes and design artefacts (Ewenstein & Whyte, 2009; Knorr Cetina, 2001). However, these epistemic objects are often difficult to describe due to their virtual nature at the edge of the participants' competence and the dynamic changes they undergo throughout the design and creation process. In this paper, we describe the team's epistemic object as comprising a cluster of concepts that unfolded through idea generation and the design problems presented by the team members during the collaborative invention process.

However, the invention process involves aspects we cannot understand merely from the perspective of the human rationalisation. Therefore, taking another, more complementary perspective brings us to focus on the active role of materiality. We draw from sociomaterial theories, which consider everything as an entanglement of social and material and trace both human and non-human interactions (Fenwick, Nerland, & Jensen, 2012). Adapting Braidotti's (2011) idea of knowing as relational, embodied and embedded allows us to perceive the invention process as thinking that cannot be separated from being. In other words, as Barad (2007) describes, the process involves knowing that emerges from direct material engagement with the world. Even inorganic material has an ability to affect (Braidotti, 2019), and the meaning of material is performed in action instead of being preformed in its fixed properties (Orlikowski, 2007). In the invention projects, new possibilities and transformations arise, and the students and materials become something that neither of them would have been by themselves (Barad, 2003). Therefore, to understand the dynamic and materially embedded intricacies of the invention projects in the field of maker-centred learning, we need to acknowledge the active role of materiality.

In the educational field, engagement with materials are perceived as allowing new ways of knowing, reading or writing (eg, Kuby, Rucker, & Kirchhofer, 2015; Thiel, 2015). The object to be learned, whether it is, for example, a mathematical concept (de Freitas & Sinclair, 2013) or a language (Toohey *et al.*, 2015) is not seen as external or fixed. Instead, learning is an indeterminate act of assembling various kinds of agencies (de Freitas & Sinclair, 2013). Open-ended and unscripted material practices can allow students to act on their own terms (Thiel, 2015) and to be

knowledgeable and competent even if they struggle with more traditional school practices, such as writing alphabetically (Toohey & Dagenais, 2015). For educators, the sociomaterial perspective helps create understanding of how objects can drive learning opportunities (Keune & Pepler, 2019) and appreciation for the seemingly chaotic moments of spontaneous play (Lenz Taguchi, 2014; Wohlwend, Pepler, Keune, & Thompson, 2017). Nonlinear co-invention projects involve multiple opportunities for spontaneous material engagement; our analysis from the sociomaterial perspective focuses especially on these encounters among humans and materials.

By combining the two (epistemic and material) perspectives, we examined learning by making with the following questions:

1. How did the design ideas evolve from preliminary, fuzzy hunches to the final ideas? What role did the materialised design artefacts play in the ideation process?
2. What kinds of shared epistemic objects did the student team build during the process, and what were its principal conceptual features?
3. How were the epistemic objects created together with non-human agencies, and how was the knowing materially entangled?

Methods

Research setting

This study is part of a larger, ongoing research project where we undertake collaborative invention projects together with several schools in Finland. The Finnish curriculum for basic education includes compulsory weekly craft lessons until grade seven. Craft education integrates design and making activities, thereby providing ample opportunities to bring together STEAM subjects (science, technology, engineering, arts and math). This approach allows us to integrate learning-by-making projects as part of regular curricular activities. This study focuses on a co-invention project we organised together with a comprehensive school located in a mainly middleclass suburban area in a large city in Southern Finland. The school is publicly funded, as all Finnish schools are, and the students live mainly in the same neighbourhood as the school. In the neighbourhood and the school, a larger percentage of the population is non-Finnish-speaking than in the city on average. All the grade seven classes in the school, a total of 70 students between the ages of 13 and 14, participated in the co-invention project.

Two craft teachers coordinated the project in collaboration with three teachers of other subjects (science, information and communication technology and visual arts) and the researchers. The open-ended design challenge given to the participants, which was collaboratively configured by the teachers and the researchers, was as follows: "Invent a smart product or a smart garment by relying on traditional and digital fabrication technologies, such as GoGo Board, other programmable devices, or 3D CAD." In February of 2018, the project started with a two-hour ideation session, arranged in collaboration with the Finnish Association of Design Learning. During this session, the students self-organised into teams and generated preliminary ideas for their inventions. Subsequently, the project involved eight to nine weekly collaborative design sessions (two to three hours per session) held in March, April and May. During these sessions, the teams collaboratively designed their inventions, tested their ideas and made prototypes. Before and during the project, the researchers familiarised the teachers with the technologies used and provided pedagogical support.

This study focuses on one of the teams whose design sessions were video-recorded during the project (for the analyses of the other four teams, see Riikonen *et al.*, 2018). The team consisted

of four boys, here assigned the pseudonyms Markus, Oliver, Leo and Joel. The four students were members of the dominant culture. After finishing sixth grade, these students had applied for their current class, the curriculum of which offers extra courses on technology education. During the project, they invented the mobile gaming grip (MGG), a pair of handles for a mobile phone to improve the ergonomics of mobile gaming. The team worked through the whole process in intensive, self-driven collaboration, with all members being highly engaged. After sketching, the team went through a two-stage process, first building a physical prototype from basic materials (ie, wood, rubber and masking tape), and then, creating 3D computer-aided design (CAD) models based on that first prototype. Their sketch and the first prototype are presented in Figures 1 and 2 respectively.

The MGG team's invention process was video-recorded for documentation. We used a GoPro action camera on a floor-standing tripod and a separate wireless microphone. A researcher was present during every session and made ethnographic observations to support an in-depth analysis of the data. The video data consisted of nine sessions, totalling 13 hours and 15 minutes of recordings.

Data analysis

We conducted the analysis in two phases with two perspectives: epistemic and material. The epistemic analysis involved two rounds of video analysis. First, we tracked the evolvement of the design ideas. Next, we analysed how an epistemic object pursued by the team was formed in the expressed design problems and the conversations preceding the ideas. The material-perspective analysis approached the video data on three levels: macro, intermediate and micro.

To analyse the evolvement of the design ideas, we systematically selected from the video all the ideas generated by the team, with the expression of a design idea as the unit of analysis. For every idea, we determined the following factors: (1) possible preliminary parent ideas or a theme to which the idea was related, (2) whether the idea was included in the final design (ie, was a final

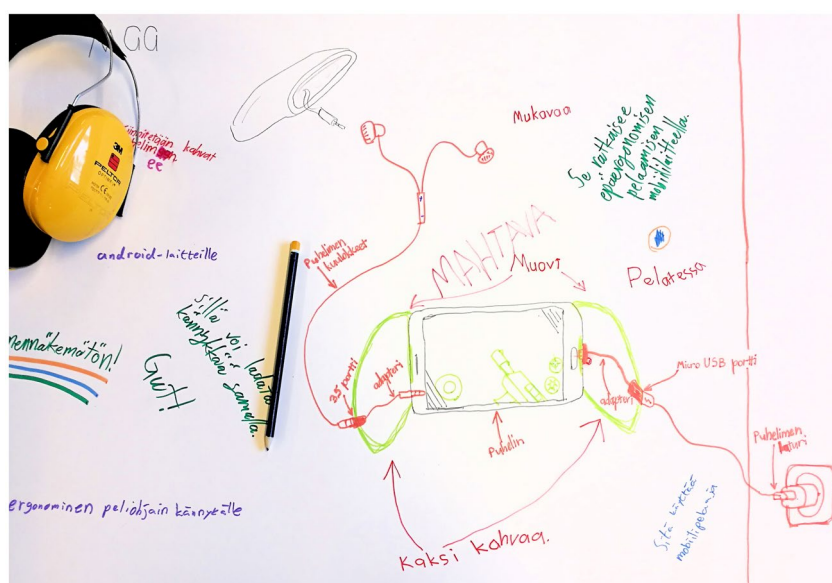


Figure 1: Sketch of the mobile gaming grip (MGG)
[Colour figure can be viewed at wileyonlinelibrary.com]



Figure 2: MGG prototype in use
 [Colour figure can be viewed at wileyonlinelibrary.com]

design idea) and (3) whether the idea was artefact mediated. To gain insights into the design artefacts' role in the ideation process, we categorised two aspects of artefact-mediated ideation: (1) the student was looking at a design artefact while generating the idea and (2) the student was holding or looking at a design artefact and pointing to or modifying it while generating the idea. Based on the analysis, a network graph of all design ideas and their evolvement was generated using the Cytoscape network visualisation software (version 3.6.0). The visualised idea network illustrated how the team members developed their ideas through an iterative process.

Through the idea evolvement analysis, we came to understand that the network of ideas revealed more profound and broader concepts of knowledge than just the design ideas. However, it did not reveal the whole nature of the team's epistemic object; while it provided the answers to the design problems, the complexity of the design problems and the epistemic work involved tended to remain hidden. We therefore conducted a second round of the video-data analysis. In this phase, we isolated the expressions of design problems and the conversations preceding the ideas, and performed a qualitative content analysis. The combination of the network of ideas and the team's epistemic object allowed us to shed light on the versatile nature of the concepts of the created knowledge.

To better understand the role of materials, we next sought to include non-human agencies in the analysis. In our efforts to empirically trace the sociomaterial aspects of the collaborative invention, we encountered two challenges: determining the relevance of the actions and building the big picture. The collected video data were rich and dense, filled with socially and materially embodied actions. Because it would have been unfruitful and nearly impossible to track each material encounter, and because our focus was on the invention process, we chose to concentrate on the materials that were relevant for the ideation or the idea refinement processes (cf. Hindmarsh & Llewellyn, 2018). However, paying attention only to small pieces of the data would pose the risk of losing the sociomaterial entanglements. Therefore, by adapting Ash's (2007) methodology, we analysed the data across three levels: macro, intermediate and micro.

On the macro level, we created an overall flowchart of the events, which allowed us to follow nonlinear trajectories and observe the central materials of the process. We chose to track three materials: the smartphone, the physical prototype and the 3D-modelling software. On the intermediate level, we focused on identifying the moments when one of the chosen materials played a role in the invention process. Rather than merely relying on predetermined categories, we sought for the moments awakening wonder, as MacLure (2013) suggests. On the micro level, we focused on reciprocal relations within the significant events. Video data allowed us to interpret both the involvement of materials in the verbal and embodied actions of the humans, as well as the placement of the material in space. Furthermore, ethnographic observations and our involvement in the learning design allowed us to consider the wider contexts. The intention of selecting the three materials was not to focus only on them. Rather, the set of selected materials acted as a starting point for the disentanglement of the process. By analysing what is entangled with an obvious material, we could also discover the more obscure sociomaterial relations appearing in the process.

Results

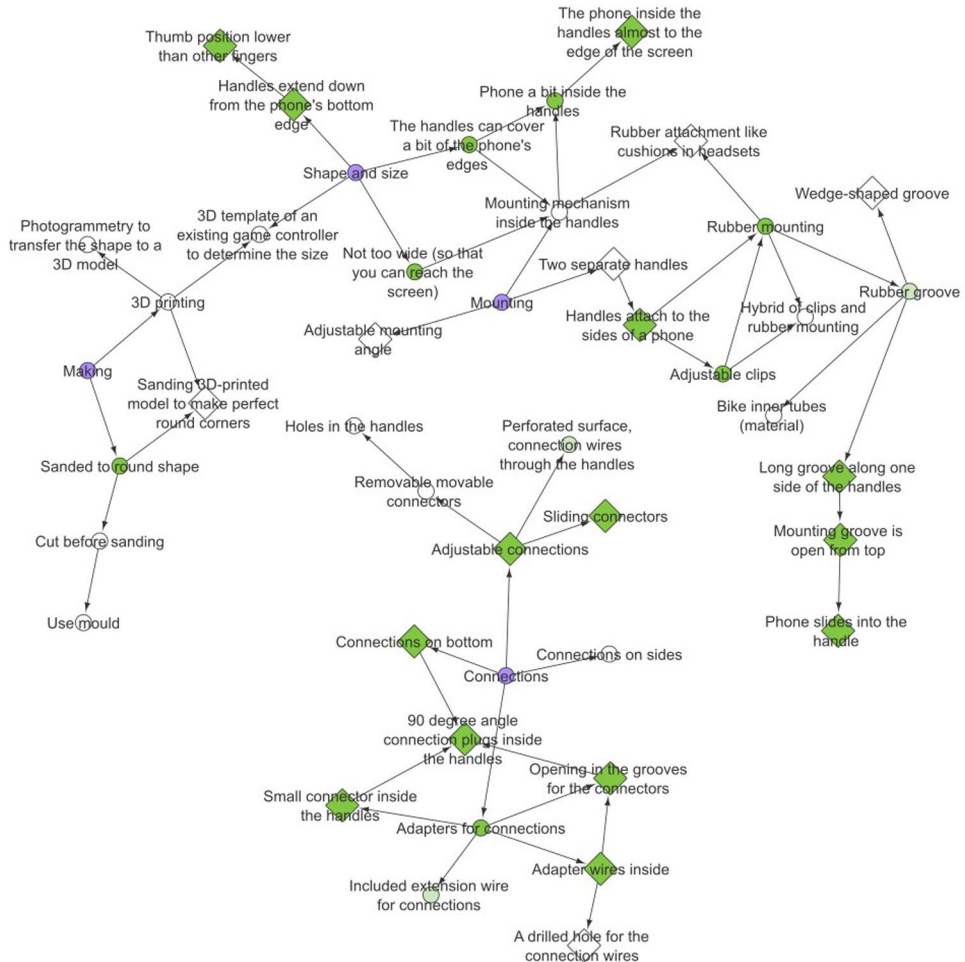
Idea generation and the themes of the shared epistemic object

The visualised network of the design ideas' evolvement (Figure 3) we created during the first round of the data analysis illustrated how the team members developed their ideas through an iterative process. The preliminary ideas, such as having two separate handles, using adapters for audio and charger connections, and using 3D printing as a method of making, triggered more refined design ideas. The network of ideas expanded around four main themes: making, shape and size, mounting and connections. The arrows in the network represent the direction of the ideation process, leading from parent ideas to new ideas. Through the process, some of the ideas across the four themes became connected. For example, some of the parent ideas were combined, such as using rubber mounting and placing the mounting mechanism inside the handles, while other ideas were rejected when new ones emerged, such as using a pair of adjustable clips as the mounting mechanism. The idea network also made visible the large number of individual ideas that were incorporated into the final invention.

Moreover, the tangible artefacts' roles in idea generation became evident from the visualisation of the idea development. The green colour in Figure 3 signifies the ideas generated while the team members were paying attention to an artefact. Of the 41 ideas generated during the process, 24 (58.5%) were artefact mediated. In most cases, the artefact was the centre of attention, being tinkered with or modified in parallel with the idea emergence. Furthermore, an even larger proportion (70%; 14 out of 24) of the ideas incorporated in the final invention were artefact mediated.

From the close collaboration within the team, as well as the members' equal participation, we read that they shared the same epistemic target object throughout the process, which they actively sought to develop together (see Paavola & Hakkarainen, 2014; Riikonen *et al.*, 2018; Seitamaa-Hakkarainen & Hakkarainen, 2001). Our second-level analysis, which focused on the epistemic object, revealed the following four interlinked themes in the team's process: *usability* of the object (adjustability, adaptability and ergonomics), *design* specifications (mounting, size and shape, structure and connections), *scientific principles* (geometry, mechanics of hand and friction), and *making* processes (materials, prototyping, 3D modelling and 3D printing). These themes, entangled together and constructed in parallel, formed the epistemic object of knowledge that the team jointly built during the process.

Next, we present excerpts from the team's discussions to describe some of the complexity and sophistication of the epistemic challenges faced by the team members during the process. For



The student was looking at the artifact while generating the idea.

The student was holding or looking at the artifact and pointing to or modifying it while generating the idea.

Idea theme that was added to the network for clarity.

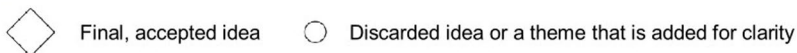


Figure 3: Network of the evolvement of design ideas and the role of design artefacts therein
[Colour figure can be viewed at wileyonlinelibrary.com]

example, in the team's process, the determination of the size of the handles was triggered by considerations of usability and the mechanics of hands. During their conversation, the members also identified two design constraints: the target group for whom the handles were meant and the limited space that would have to hold the mounting mechanism attaching the handles to a mobile phone. This conversation demonstrates the intertwined nature of the concepts that formed the team's epistemic objects, as well as the versatility in thinking that was required during the co-invention process.

Oliver: We should think about the size... if it were here, like, this [gestures to others to demonstrate the size and shape], could you still reach the screen easily enough?

Others: Yes, maybe

Oliver: So, then it should be about, like this [draws a shape around his phone].

Joel: It's not usual to have something important in the middle of the screen. Although in Geometry Dash, there is that practice thing there

Oliver: I don't know if that matters. Who plays Geometry Dash with these, anyway? I think that these are more, like, for driving games and for FPS games that you can't play conveniently on a mobile phone.

Oliver: Now, if it's like this, we have this much space for the things that will hold the handles in place. So, we need something like...

The second example demonstrates the characteristics of the co-invention process, the artefacts' role in the ideation process, and how a scientific concept (friction) becomes incorporated in the process. In the co-invention processes, the support provided by the teachers was essential, and this conversation occurred between one team member and the teacher. Other team members were present during the conversation and joined in at a later stage. The conversation revealed how a seemingly unrelated artefact, a hearing protector headset (Figure 4), served as a source of inspiration for the rubber mounting system of the handles. The teacher's expertise then enabled the idea to be transformed into a practical design solution.

Oliver: We thought we would do something like this. We need something that, you know, holds the handles in place. We think it could be something like this, that the phone fits into, and it holds the phone in place [demonstrates the idea by inserting the phone between the ear cushions of a hearing protector headset; see Figure 4].

Teacher: Yes...

Oliver: But we don't know how to make it yet

Teacher: It could be rubber... some sort of grooves. We could try to make those from a bike inner tube or something like that. Like, if you push the phone in, friction holds it in place. Could it be wedge-shaped?

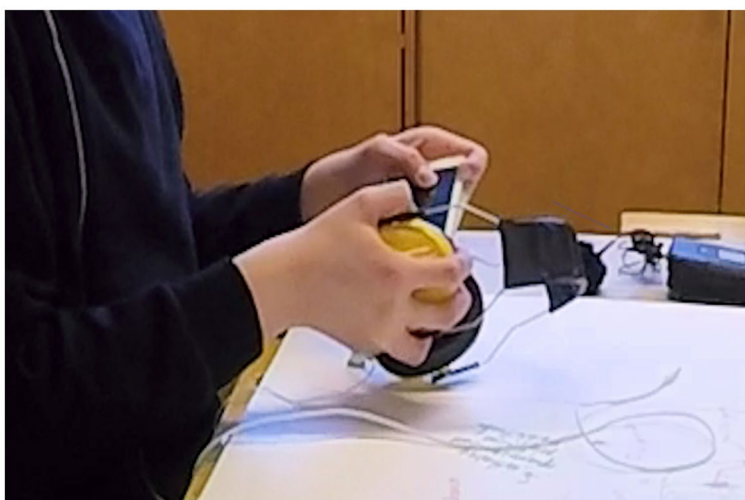


Figure 4: A team member tinkering with his phone and a hearing protector headset [Colour figure can be viewed at wileyonlinelibrary.com]

Also, the analysis revealed how the team was able to identify design problems and how concrete artefacts helped the members to further define problems. For example, the team could have designed the handles for only one phone model; instead, they chose to seek an adjustable solution. Simultaneously, the generation of the design ideas and the creation of the epistemic objects were fundamentally entangled with the materiality of creative activity. We focused on the relations of these human and non-human aspects in the next phase of our analysis presented in the following section.

Epistemic role of materiality in the invention process

An uncomfortable smartphone gaming experience was the starting point for the team's idea. However, the creation of the new artefact was not affected only by human design intentions and properties of smartphones, but also by other materials of the making process, such as material resources of the classroom, making tools and other artefacts and the time allocated for the project. These aspects were constantly in a relationship with one another, with the idea itself, and with the makers' skills and experiences. Next, we demonstrate these entanglements with excerpts from the data.

The physical and virtual properties of smartphones and existing gaming grips set constraints for the process, yet also offered steppingstones for generating novel ideas. In the beginning of the project, the students mentioned the handles of a PlayStation controller as a possible inspiration for the size of their product, and their discussion suggested that all team members had previous experiences with various video gaming devices. In the following excerpt, one of the students reflects on his former experiences regarding good and poor qualities of gaming grips. The excerpt illustrates how the MGG's form and functions depended on the properties of smartphones and were informed by the properties of existing gaming grips.

Oliver [holding a smartphone]: For example, I have one of those, not grips, but like... buttons. Its idea is that you can play. But there is the problem that you can't use the headphones or charge the phone at the same time. It kind of goes around this [gestures toward the smartphone] so that you have to play like... And it covers the speakers.

Simultaneously, the invention process relied on limited resources. The classroom had only certain materials and equipment, and the project duration was restricted. The team members had various making skills, which affected not only what they could create with the available materials, but also the nature and the number of features they could imagine the materials to have. The ideas did not solely determine what the team could make, nor did the materials as such dictate the making options. Rather, the materials, time, ideas and skills either constrained or allowed various possibilities. In the following conversation, the students search for the balance between the design idea and the practicalities of making.

Oliver: If we choose the rubber thing and it only reaches this far [puts a smartphone inside a hearing protection headset and shakes them], then the phone moves quite a lot. That's a problem.

Joel: But the clips are much harder to make

Oliver: Yeah, but it is nicer

Joel: Especially if we do the whole thing with 3D printing, it will be hard to make the clips. From that point of view, we would get off easier...

Oliver: But I don't know if it is that good, considering the usability

The details of the gaming grip became refined when the team moved into the modelling process. The material-making task allowed abstract ideas to become tangible, thus pushing the students to design not only verbally, but also together with the materials. The following conversation was

preceded by the team having decided to make a universal model with an adjustable audio connector. During the making process, the wooden model concretised the constraint regarding the size of the audio plug, while existing audio plugs set demands for the dimensions of the handles. In the excerpt below, the existing audio-plug artefacts became involved in the process through the students' and their teacher's past experiences. The teacher's knowledge and the material resources available made it possible for a suitable plug to be physically included. The small plug ended the discussions about audio connections for the time being and allowed the team to proceed with the model making.

Oliver [looking at and twisting the wooden model in his hands]: *Now, when you look at this. Here would be the hole for the audio plug [...]. But is there any space for an audio plug anymore?*

Leo: *And that really must be there because the audio connection is one of the most important things*

[...]

Teacher: *Just as a brainstorming idea—what if the handle had as many holes as possible, so one could plug the headphones straight in there?*

Oliver: *But there is only the problem that many audio plugs... For example, I have one that is really long. So, that's why it would be good that the adapter wire would be inside there, so that one could plug any headphones to this.*

Leo: *And I have one of those that has a... erm... turning thing [draws a 90-degree angle on the air].*

[...]

Oliver: *The issue now is... does a small enough audio plug even exist?*

[The teacher goes to the other room and comes back with a small audio plug.]

Oliver: *Yeah, this will fit. This works*

In addition to intentional designing, the unscripted sessions also enabled spontaneous play and non-task-related experimentation with the materials. The two computer screens shown in Figure 5 illustrate a non-task-related and a task-related 3D-model. Joel, on the right, was creating

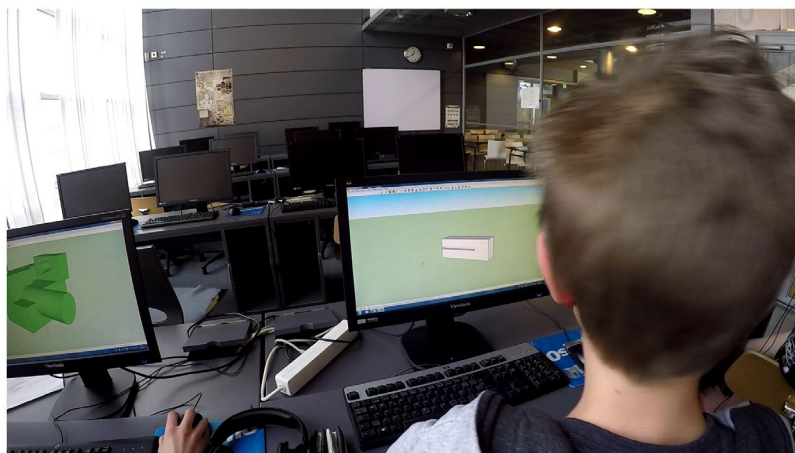


Figure 5: On the left, Leo's non-task-related 3D model; on the right, Joel's half-finished model of the gaming grip [Colour figure can be viewed at wileyonlinelibrary.com]

a model of the MGG. During the time of this screen capture, he was looking for a solution to making rounded edges. On the left, Leo's intentions appeared to be in experimenting and playing, and different properties of the same software emerged in his model. In the vignette below, the teacher's making skills and task-related intentions interconnect the two 3D-models and encourage the students to apply the properties of Leo's playing-around model to Joel's gaming-grip model.

Joel took the main responsibility for making the 3D model; others engaged in off-task activities, such as playing around with the 3D-modeling software, SketchUp, or surfing the Internet. Joel tried to model the gaming grip according to the measurements they had decided on with the wooden model, but he quickly ran into a problem: how to make rounded edges with SketchUp. He purposefully tested different features of the software but could not find a solution. Next to Joel, Leo was making non-task-related 3D models. Joel pointed out the problem to the teacher, who went to stand next to Leo's screen and said, "What about what Leo is doing here? You can see the solution there". The teacher then manipulated Leo's non-task-related 3D model to emphasize how the model combined straight and round shapes.

The analysis from the material perspective revealed various sociomaterial entanglements of human and non-human agencies. Smartphones and existing gaming grips served as stepping-stones and guidelines by inspiring the shape of the invention and providing design constraints. The entanglement of the materials in the classroom, the students' making skills, and the available time outlined the direction of the knowledge-creation process. This direction was evident when the team decided the making methods based on the available materials and the members' abilities in using them. Additionally, the team considered the details in the model-making phase, where the tangible model made evident the details needing refinement, such as the precise placement and size of the audio connectors. When foregrounding the material aspect, we were able to recognise a moment of knowledge creation in the seemingly non-task-related action of playing with the 3D-modelling software. Altogether, the materials alone did not determine the advancement of the team, but they did appear as active and meaningful co-participants in the invention process.

Discussion and conclusion

In this study, we aimed to analyse and describe the following: (1) How did the design ideas evolve from preliminary fuzzy hunches to the final ideas? What role did the materialised design artefacts play in the ideation process? (2) What kinds of shared epistemic objects did the student team build during the process and what were the principal conceptual features? (3) How were the epistemic objects created together with non-human agencies, and how was the knowing materially entangled? We then conducted the analysis from two perspectives: epistemic and material.

The visualised network of idea evolvment (Figure 3) illustrates the multifaceted and iterative nature of the team's idea generation process. Ideas were generated, analysed and accepted or rejected during the ideation process. Furthermore, the ideas evolved through an iterative process of combining and modifying design ideas. Although the team's co-invention may seem simple, creating the MGG required a significant amount of innovative thinking and solving of complex design problems. Generating the final design ideas took several stages of ideation around multiple themes. The number of individual design ideas that formed the final invention further signifies the intensity of the epistemic efforts required to create the MGG. The design artefacts' role in the ideation process suggests their important function in stimulating ideation and knowledge creation (cf. Ewenstein & Whyte, 2009; Knorr Cetina, 2001; Paavola & Hakkarainen, 2014). The artefact-mediated nature of the ideas that were incorporated into the final design was particularly informative, signifying the essential role of artefacts and actual making when ideas are being improved, refined and advanced.

When taking the material perspective, we considered materials as more than mediators and aimed at including non-human agencies in the analysis. This approach highlighted the active role of materiality for idea refinement, as various artefacts involved in the process affected which questions could be asked during the design process. The artefacts resembled the instruments of a science classroom in terms of their effect on what kind of knowledge can be produced (Barad, 2007; Milne, 2019). For instance, the constitutive entanglement (Barad, 2007) of human and non-human components was apparent in the ideation of the audio connections. If the MGG had been designed a few years later, as smartphones generally have no physical audio connectors now, the design object and process would have changed as well. The importance of artefacts that were not physically present was also detectable. The shape of existing gaming controllers and usability of existing mobile gaming accessories participated in the ideation process through the students' former material experiences. This illustrates how the invented object, the MGG, was not isolated from other objects, nor was the ideation process only a human process; the project allowed space for the material artefacts to connect the process to the wider world (Braidotti, 2019).

Our understanding of the team's epistemic object began to emerge from the network of idea evolvement. When the epistemic object was combined with the expressions of design problems and the conversations preceding the ideas, we were able to frame it with four interlinked concepts: usability of the artefact, design specifications, scientific principles and making processes. It is interesting how versatile and sophisticated the considered epistemic issues were, ranging from practical making to theoretical scientific concepts. The fact that the team took on epistemic challenges beyond what was required or necessary is a significant finding. Being able to identify principal elements of the team's epistemic object helps us consider what kind of learning occurs during maker-centred co-invention processes.

With the material perspective, we shed light on the indeterminacy of the process, illustrated by the many strands in the network of idea evolvement (Figure 3) and the versatility of epistemic objects. The open-ended design task allowed the students to play around with different options, and the end goal of the process, the invention, was constantly changing and reforming. However, the material making rooted the process to the tangible world, illustrating the embeddedness of thinking (Braidotti, 2011). For instance, the students had to balance their competences, the material resources and the idea itself when considering which mounting mechanism to choose. Shifting the emphasis from representational skills to embodied performative skills allowed for a more effective approach (Braidotti, 2019). The team could not act only on the level of language and human rationalisation; instead, they were invited to think together with materials.

Moreover, we identified moments when materials invited students to play (Lenz Taguchi, 2014), as in the case of the 3D-modelling software (Figure 5). The unscripted schedule, as well as the flexible division of labour, allowed for these spontaneous, non-task-related experimentations with the materials; there was space for students to be affected by the non-living materials (Braidotti, 2011). If we consider knowing not as reasoning from the position of an outside observer but as being with the world (Barad, 2003), we can frame the moment of playing as experiencing and knowing geometrical shapes and the software in action. Similar knowing with the materials is illustrated in the example wherein a student is experiencing friction together with a smartphone and a hearing protector (Figure 4), forming an interdependent human-material entanglement (Barad, 2007). In this case, the meaning of the hearing protection headset's materiality appears as not preformed, but performed in action (Orlikowski, 2007). Previous educational studies adapting a posthumanist perspective (eg, Kuby *et al.*, 2015; Thiel, 2015; Toohey & Daegenais, 2015; Wohlwend *et al.*, 2017) have also emphasised the meaning of engaging with materials and argued that knowing and learning can be defined as more than mere strategic sense-making.

Our study illustrates the versatile, epistemic challenges and the opportunities for knowledge creation that a co-invention project can offer. During the project, open access to rich material resources (Keune & Pepler, 2019; Thiel, 2015), an open-ended design task, and unscripted sessions provided possibilities to think and know together with materials. The two perspectives of analysis, epistemic and material, provided complementary insights into the intricacies of the invention process. In order to develop the practices of co-invention projects, further research from both perspectives will be needed. Furthermore, the future studies should acknowledge wider social aspects, such as opportunities for access to materials and technologies. In addition to developing the sociomaterial research, it is important to consider how the embedded and embodied knowing could be promoted in educational practices.

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Author contributions

Mehto and Riikonen have equal contribution of the study: they collected and developed methods used in data analysis together. They were also responsible for analysis of the data and the interpretation of the results. Seitamaa-Hakkarainen, Kangas and Hakkarainen provided theoretical and methodological guidance during the writing process and all contributed to writing of the manuscript.

Statements on open data, ethics and conflict of interest

This research was conducted following the guidelines of the Finnish National Board on Research Integrity (TENK).

Informed consent was obtained from participants and their guardians. The consent obtained from the participants limits the usage of the data strictly to the researchers participating in the Growing Mind research project only. Therefore, the data cannot be made available upon request. The authors have no conflict of interest.

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